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Comments on Recent Measurements of R_c and R_b

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Abstract

Discrepancies between Standard Model predictions and experimental measurements of the fractions R_c and R_b of hadronic Z decays to charm and bottom are investigated. We show that there exists a discrepancy in two complementary determinations of $B(\overline{B} \to DX)$. Reducing the branching ratio $B(D^0 \to K^-\pi^+)$ by $\sim 15\%$ from currently accepted values to $(3.50 \pm 0.21)\%$ removes the discrepancy. Since $B(D^0 \to K^-\pi^+)$ calibrates most charmed hadron yields, the reduced value also eliminates the discrepancy between the predicted and measured values of R_c and mitigates a problem in semileptonic B decays. A reduction in $B(D^0 \to K^-\pi^+)$ would also mean that roughly 15% of all D^0 and D^+ decays have not been properly taken into account. It is shown that if the missing decay modes involve multiple charged particles, they would be more likely to pass the requirements for lifetime B tagging at LEP and SLC. This would mean that the charm tagging efficiency in $Z \to c\bar{c}$ has been underestimated. As a consequence R_b would need to be revised downward, potentially bringing it in line with the Standard Model prediction.

I. INTRODUCTION

Recent discrepancies between theoretical predictions and experimental measurements of the fractions R_c and R_b of hadronic Z decays to charm and bottom [1,2] could have very serious implications for the Standard Model. It is therefore extremely important to determine whether or not there exist possible explanations for these discrepancies which do not contradict the current paradigm. To this end we show in Section II that there now exist two complementary determinations of $B(\overline{B} \to DX)^*$. After making reasonable adjustments to charmed baryon yields, we show that the two estimates disagree. We find that a 15% reduction in $B(D^0 \to K^-\pi^+)$ to $(3.50 \pm 0.21)\%$ eliminates the problem. We then proceed to demonstrate that reducing $B(D^0 \to K^-\pi^+)$ also eliminates the discrepancy between the predicted and measured values of R_c and alleviates a problem in semileptonic B decays. One further consequence of the change in $B(D^0 \to K^-\pi^+)$ would be that roughly 15% of all D^0 and D^+ decays have not been properly taken into account. In Section III we show that if these missing decay modes involve multiple charged particles, they would be more likely to pass the requirements for lifetime B tagging at LEP and SLC. In this case, the charm tagging efficiency in $Z \to c\bar{c}$ events would have been underestimated. This would necessitate a downward revision in the measured value of R_b which would bring it closer to the Standard Model prediction. The effect could in fact be large enough to completely eliminate the R_b discrepancy.

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*Throughout this note, CP violation is neglected and for each process its CP-conjugate is implied.

II. R_c MEASUREMENTS AND $B(D^0 \to K^-\pi^+)$

The fraction R_c of hadronic Z decays to charm, which is predicted to be 0.172 in the Standard Model, has recently been measured to be 0.1598 ± 0.0069 [1,2]. Similarly, the number of charm quarks per B decay (n_c) was historically measured to be smaller than expected [3], especially in view of the small measured inclusive semileptonic B decay branching ratio. Furthermore, the sum over all branching ratios of exclusive semileptonic B decays falls significantly short of the inclusive $B(B \to X\ell\nu)$ measurements [4].

One possible explanation for these discrepancies is that a systematic under-counting of charm has taken place. In particular, a common thread in these measurements is a significant reliance upon the measured value of $B(D^0 \to K^-\pi^+)$ to calibrate charm production and decay for a wide range of observable decay modes. The CLEO experiment measures [5]

$$B(D^0 \to K^-\pi^+) = (3.91 \pm 0.19)\% \ ,$$

and the 1994 Particle Data Group [6] cites a world average of

$$B(D^0 \to K^-\pi^+) = (4.01 \pm 0.14)\% \ .$$

These calibrate not only the D^0 decay modes, but the D^+ decay modes as well [7], via the ratio

$$r_+ \equiv \frac{B(D^+ \to K^-\pi^+\pi^+)}{B(D^0 \to K^-\pi^+)} \ .$$

The calibration mode for D_s, namely $B(D_s \to \phi\pi)$, has also recently been tied to $B(D^0 \to K^-\pi^+)$ in a model-independent fashion [8].

As a result of a recent measurement by CLEO [9] of the wrong-charm production in flavor-tagged B decays, it is now possible to determine the right-charm branching fraction, $B(\overline{B} \to DX)$, in two complementary ways. As one important consequence, we can treat $B(D^0 \to K^-\pi^+)$ as an unknown which is determined by equating the two results for $B(\overline{B} \to DX)$. This exercise is carried out in the next section after we address several concerns related to charmed baryon yields which result in an overall reduction in the estimate for weakly decaying charmed baryon production in B decays.

A. Inclusive D Yields in $\overline{B}$ Decays and $\mathbf{B(D^0 \to K^-}\pi^+)$

The number of charmed hadrons per B decay is defined as

$$n_c \equiv Y_D + Y_{D_s} + Y_{baryon_c} + 2B(\overline{B} \to (c\bar{c})X) \ , \tag{2.1}$$

where the inclusive production of final states containing an arbitrary charmed hadron T is defined by

$$Y_T \equiv B(\overline{B} \to TX) + B(\overline{B} \to \overline{T}X) \ . \tag{2.2}$$

The weakly decaying, singly charmed baryon species $(\Lambda_c, \Xi_c^{+,0}, \Omega_c)$ are collectively denoted by $baryon_c$ while $(c\bar{c})$ represents charmonia not seen as open charm. Table I summarizes CLEO measurements with the underlying calibration terms factored out explicitly. Note that the inclusive D^+ yield in B decays involves $B(D^+ \to K^-\pi^+\pi^+)$ which is calibrated by $D^0 \to K^-\pi^+$ [7] via the ratio,

$$r_+ \equiv \frac{B(D^+ \to K^-\pi^+\pi^+)}{B(D^0 \to K^-\pi^+)} = 2.35 \pm 0.23 \ . \tag{2.3}$$

We can thus express Y_{D^+} in terms of $B(D^0 \to K^-\pi^+)$ as

$$\begin{aligned} Y_{D^+} &= (0.235 \pm 0.017)\ \frac{9.3\%}{B(D^+ \to K^-\pi^+\pi^+)} = \\ &= (0.235 \pm 0.017)\ \frac{9.3\%}{r_+ \cdot B(D^0 \to K^-\pi^+)} = \\ &= (0.238 \pm 0.029)\ \left[\frac{3.91\%}{B(D^0 \to K^-\pi^+)}\right] \ . \end{aligned} \tag{2.4}$$

The inclusive D yield in $\overline{B}$ decays,

$$Y_D \equiv Y_{D^0} + Y_{D^+} \ , \tag{2.5}$$

can then be expressed in terms of $B(D^0 \to K^-\pi^+)$ as shown in Table I.

The central values for Ξ_c and Λ_c yields which are typically used in the determination of n_c are both at the 5% level [10]. The inclusive Λ_c production in B decays is measured rather well, whereas the Ξ_c yield has large uncertainty. The CLEO experiment has demonstrated

that right-sign $\ell^+\Lambda_c$ correlations dominate over the wrong-sign $\ell^-\Lambda_c$ case [11], (where the lepton comes from the semileptonic decay of one B and the Λ_c originates from the other B in an $\Upsilon(4S)$ event). As a consequence, inclusive Ξ_c production in B decays cannot be as large as that of the Λ_c. This is shown in the Appendix where we relate both Ξ_c and Ω_c production in B decays to Y_{Λ_c} and the ratio

$$r_{\Lambda_c} \equiv \frac{B(\overline{B} \to \overline{\Lambda}_c X)}{B(\overline{B} \to \Lambda_c X)} \ . \tag{2.6}$$

We neglect $b \to u$ transitions and use the Cabibbo suppression factor, $\theta^2 = (0.22)^2$, for charmed baryon production in $b \to c\bar{u}s(b \to c\bar{c}d)$ versus $b \to c\bar{u}d'(b \to c\bar{c}s')$. [The prime indicates that the corresponding Cabibbo-suppressed mode is included.] The Appendix also parametrizes $s\bar{s}$ fragmentation from the vacuum, and predicts

$$\frac{Y_{\Xi_c}}{Y_{\Lambda_c}} = 0.38 \pm 0.10 \ , \tag{2.7}$$

$$\frac{Y_{baryon_c}}{Y_{\Lambda_c}} = 1.41 \pm 0.12 \ , \tag{2.8}$$

$$\frac{B(\overline{B} \to baryon_c X)}{Y_{\Lambda_c}} = 1.22 \pm 0.07 \ , \tag{2.9}$$

$$\frac{B(\overline{B} \to \overline{baryon_c}\, X)}{Y_{\Lambda_c}} = 0.20 \pm 0.10 \ . \tag{2.10}$$

As discussed in the Appendix, Ξ_c production in $\overline{B}$ decay is probably overestimated. Inclusive $baryon_c$ production thus lies somewhere in the range

$$1 < \frac{Y_{baryon_c}}{Y_{\Lambda_c}} < 1.41 \pm 0.12 \ . \tag{2.11}$$

Variation over this range has negligible effect on the value of n_c. We therefore use the values given in Eqs. (2.7) - (2.10). We also prefer not to use the 1994 PDG value [6] of $B(\Lambda_c \to pK^-\pi^+) = (4.4 \pm 0.6)\%$, because it relies upon a flawed model of baryon production in B decays. We instead follow the approach outlined in Ref. [12] and use $B(\Lambda_c \to pK^-\pi^+) = (6.0 \pm 1.5)\%$. Thus n_c in Eq. (2.1) can be written :

$$n_c = (0.883 \pm 0.038) \left[\frac{3.91\%}{B(D^0 \to K^-\pi^+)}\right] + (0.1211 \pm 0.0096) \left[\frac{3.5\%}{B(D_s \to \phi\pi)}\right] + \\ + (0.042 \pm 0.008) \left[\frac{6\%}{B(\Lambda_c \to pK^-\pi^+)}\right] + 2B(\overline{B} \to (c\bar{c})X) \ . \tag{2.12}$$

Inserting the branching fractions in Table II and estimating [13],

$$B(\overline{B} \to (c\bar{c})X) = 0.026 \pm 0.004 \ , \tag{2.13}$$

one obtains

$$n_c = 1.10 \pm 0.06 \tag{2.14}$$

which is below the currently accepted value of 1.18 ± 0.06 [10].

Very recently, the CLEO experiment has completed the direct measurement of $B(b \to c\bar{c}s')$ which allows one to use the following, alternative expression for the number of charm quarks per B decay [13],

$$\tilde{n}_c = 1 - B(b \to \text{ no charm}) + B(b \to c\bar{c}s') \ . \tag{2.15}$$

This expression is much less sensitive to either $B(\overset{(-)}{B} \to baryon_c X)$ or $B(D^0 \to K^-\pi^+)$. We take $B(b \to \text{no charm})$ to be [13],

$$B(b \to \text{ no charm}) = (0.25 \pm 0.10)\ (0.1049 \pm 0.0046) = \\ = 0.026 \pm 0.010. \tag{2.16}$$

The inclusive wrong charm B decay branching fraction is expressed as [13–15]

$$B(b \to c\bar{c}s') = B(\overline{B} \to \overline{D}X) + B(\overline{B} \to D_s^- X) + \\ + B(\overline{B} \to \overline{baryon}_c\, X) + B(\overline{B} \to (c\bar{c})X) \ . \tag{2.17}$$

From Tables I and III, Eq. (2.17) and the charmed baryon correlations discussed in the Appendix, we thus obtain

$$B(b \to c\bar{c}s') = (0.085 \pm 0.025) \frac{3.91\%}{B(D^0 \to K^-\pi^+)} \\ + (0.100 \pm 0.012) \left[\frac{3.5\%}{B(D_s \to \phi\pi)}\right] + (0.0059 \pm 0.0031) \left[\frac{6\%}{B(\Lambda_c \to pK^-\pi^+)}\right] \\ + B(\overline{B} \to (c\bar{c})X) \ . \tag{2.18}$$

Using the absolute charm branching fractions of Table II we obtain

$$B(b \to c\bar{c}s') = 0.22 \pm 0.03 \ , \tag{2.19}$$

$$\tilde{n}_c = 1.19 \pm 0.03 \ . \tag{2.20}$$

The quantities n_c and $\tilde{n}_c$ must be equal. Their difference can be traced to a significant discrepancy in two alternative determinations of $B(\overline{B} \to DX)$. On the one hand, one can write

$$\begin{aligned} B(\overline{B} \to DX) = 1 - B(\overline{B} \to \text{ no charm}) - B(\overline{B} \to D_s^+ X) + \\ - B(\overline{B} \to baryon_c X) - B(\overline{B} \to (c\bar{c})X) \ . \end{aligned} \tag{2.21}$$

Inserting the values from Eqs. (2.13) and (2.16) and the current CLEO results,

$$B(\overline{B} \to D_s^+ X) = (0.021 \pm 0.010) \left[\frac{3.5\%}{B(D_s \to \phi\pi)} \right] \ , \tag{2.22}$$

$$B(\overline{B} \to baryon_c X) = (0.0365 \pm 0.0065) \left[\frac{6\%}{B(\Lambda_c \to pK^-\pi^+)} \right] \ , \tag{2.23}$$

into the right hand side of Eq. (2.21) we obtain

$$B(\overline{B} \to DX) = (0.89 \pm 0.02) \ \ . \tag{2.24}$$

On the other hand, current CLEO measurements of Y_D and r_D (see Tables I and III) yield,

$$B(\overline{B} \to DX) = (0.798 \pm 0.042) \left[\frac{3.91\%}{B(D^0 \to K^-\pi^+)} \right] \ . \tag{2.25}$$

Equating the two determinations of $B(\overline{B} \to DX)$,

$$(0.89 \pm 0.02) = (0.798 \pm 0.042) \left[\frac{3.91\%}{B(D^0 \to K^-\pi^+)} \right] \ , \tag{2.26}$$

it follows that either the coefficient (0.798 ± 0.042), or $B(D^0 \to K^-\pi^+) = \ (3.91 \pm 0.19)\%$, or both, are incorrect. Let us assume for the moment that only $B(D^0 \to K^-\pi^+)$ is incorrect. We can then solve Eq. (2.26) for $B(D^0 \to K^-\pi^+)$ to obtain,

$$B(D^0 \to K^-\pi^+) = (3.50 \pm 0.21)\% \ . \tag{2.27}$$

This is considerably smaller than currently accepted values but compatible with the most recent measurement from ARGUS [16],

$$B(D^0 \to K^-\pi^+) \ = \ (3.41 \pm 0.12 \pm 0.28)\%.$$

Eq. (2.27), in turn, yields

$$B(b \to c\bar{c}s') = (22.7 \pm 3.5)\% \ , \tag{2.28}$$

$$n_c = \tilde{n}_c = 1.20 \pm 0.04 \ . \tag{2.29}$$

Our result must of course be corroborated by additional precision studies. In the meantime we have investigated some consequences of a lower value for $B(D^0 \to K^-\pi^+)$.

B. The Low R_c Measurement

Whereas theory predicts

$$R_c \equiv \frac{\Gamma(Z^o \to c\bar{c})}{\Gamma(Z^o \to \ \text{hadrons})} = 0.172 \ , \tag{2.30}$$

experiments yield a combined result which is $\sim 2\sigma$ lower [1]

$$R_c|_{exp} = 0.1598 \pm 0.0069 \ . \tag{2.31}$$

To analyze this result one must make distinctions among the various contributing measurements. Those which fully reconstruct a primary D^{*+} are calibrated by $B(D^o \to K^-\pi^+)$. These are [17,18]

$$R_c(DELPHI \ D^*) = 0.148 \pm 0.007 \pm 0.011 \ , \tag{2.32}$$

$$R_c(OPAL \ D^*) = 0.1555 \pm 0.0196 \ , \tag{2.33}$$

with a world-average of

$$R_c(D^*) = 0.150 \pm 0.011 \ . \tag{2.34}$$

Unfortunately, the uncertainty in R_c measurements due to $B(D^o \to K^-\pi^+)$ has not been explicitly reported. We therefore conservatively retain the full error on R_c to write

$$0.172 = (0.150 \pm 0.011) \left[\frac{3.84\%}{B(D^o \to K^-\pi^+)} \right] \ . \tag{2.35}$$

(Note that the calibration factor is different than that used previously because these measurements have taken the updated PDG value [20] $B(D^o \to K^-\pi^+) = (3.84 \pm 0.13)\%$.) This yields

$$B(D^o \to K^-\pi^+) = (3.35 \pm 0.25)\% \ , \tag{2.36}$$

which is near to the value we extracted in Eq. (2.27).

Note that DELPHI has also measured R_c via an inclusive double tag method, where only the daughter pion of the $D^{*\pm}$ is identified. This method does not involve $B(D^o \to K^-\pi^+)$ and the result [1,17], albeit of limited precision,

$$R_c(\pi^+\pi^-) = 0.171^{+0.014}_{-0.012} \pm 0.015 \tag{2.37}$$

agrees well with the Standard Model.

Other measurements of R_c include a lepton method which has very large systematic uncertainties, and measurements from both OPAL and DELPHI that involve direct charm counting [1,19]. The extraction of $B(D^o \to K^-\pi^+)$ from the latter is less straightforward since a variety of charmed hadrons are involved. Consider, for instance, the recent OPAL result [19],

$$R_c(\text{charm counting}) = 0.167 \pm 0.011(stat) \pm 0.011\ (sys) \pm 0.005\ (br) \ . \tag{2.38}$$

OPAL measures

$$R_c\, f(c \to D^o)\, B(D^o \to K^-\pi^+) = (0.389 \pm 0.037)\% \,,$$

$$R_c\, f(c \to D^+)\, B(D^+ \to K^-\pi^+\pi^+) = (0.358 \pm 0.055)\% \,,$$

$$R_c\, f(c \to D_s^+)\, B(D_s^+ \to \phi\pi^+) = (0.056 \pm 0.017)\% \,,$$

$$R_c\, f(c \to \Lambda_c^+)\, B(\Lambda_c^+ \to pK^-\pi^+) = (0.041 \pm 0.020)\% \,. \tag{2.39}$$

The fractions are summed by using the updated PDG branching fractions [20] as reference:

$$B(D^o \to K^-\pi^+) = (3.84 \pm 0.13)\% \,,$$

$$B(D^+ \to K^-\pi^+\pi^+) = (9.1 \pm 0.6)\% \,,$$

$$B(D_s^+ \to \phi\pi^+) = (3.5 \pm 0.4)\% \,,$$

$$B(\Lambda_c \to pK^-\pi^+) = (4.4 \pm 0.6)\% \,. \tag{2.40}$$

They assume that the undetected primary Ξ_c and Ω_c production is $(15 \pm 5)\%$ of the primary Λ_c production, and thus obtain Eq. (2.38).

We assume the standard model value $R_c = 0.172$ and again use the more accurate estimate for $B(\Lambda_c \to pK^-\pi^+)$ of $(6.0 \pm 1.5)\%$, rather than $(4.4 \pm 0.6)\%$, in order to solve for $B(D^o \to K^-\pi^+)$. We correlate the inclusive primary production fraction of $baryon_c$ to that of Λ_c via

$$f(c \to baryon_c) = \; f(c \to \Lambda_c) \;/\; (1-p)^2 \,, \tag{2.41}$$

where p models the production fraction of $s\bar{s}$ fragmentation relative to $f\bar{f}$ fragmentation from the vacuum, ($f = u, d$ or s) [21]. The solution for $B(D^o \to K^-\pi^+)$ is

$$B(D^o \to K^-\pi^+) = \frac{(0.00389 \pm 0.00037) + \frac{0.00358 \pm 0.00055}{r_+}}{R_c - \frac{(0.00056 \pm 0.00017)}{B(D_s \to \phi\pi^+)} - \frac{(0.00041 \pm 0.00020)}{(1-p)^2 B(\Lambda_c \to pK^-\pi^+)}} \,. \tag{2.42}$$

Inserting,

$$r_+ = 2.35 \pm 0.23, \quad R_c = .172, \quad B(D_s \to \phi\pi^+) = (3.5 \pm 0.4)\% \,, \tag{2.43}$$

$$\text{and } B(\Lambda_c \to pK^-\pi^+) = (6.0 \pm 1.5)\%, \tag{2.44}$$

we obtain

$$B(D^o \to K^-\pi^+) = (3.67 \pm 0.36)\% \ . \tag{2.45}$$

C. Semileptonic B Decays

Semileptonic B transitions are among the most intensively studied B decays. They consist almost entirely of $b \to c\ell^-\bar{\nu}$ transitions, since $|V_{ub}/V_{cb}| \approx 0.1$. Thus a primary lepton in B decay is typically accompanied by a charmed hadron. Inclusive semileptonic B decay measurements detect the lepton without reconstructing the accompanying charmed hadron. As a result, uncertainties from charm are minimal. These measurements also usually involve very high statistics and so they are generally very precise [2,22–24].

A variety of semileptonic B decay measurements, where the accompanying charm was also seen, have been reported [22]. These include the dominant exclusive $\overline{B} \to D^{(*)}\ell^-\bar{\nu}$ processes, $\overline{B} \to D^{**}(X)\ell^-\bar{\nu}$ transitions, and non-resonant $\overline{B} \to D^{(*)}\pi X\ell^-\bar{\nu}$ processes. Combining all information about semileptonic B decay measurements where the associated charm is also seen, one finds a significant shortfall relative to the inclusive measurements [4]. Decreasing $B(D^0 \to K^-\pi^+)$ would alleviate this shortfall, because the semileptonic branching fractions with reconstructed charm are inversely proportional to $B(D^0 \to K^-\pi^+)$ and would therefore increase. With some theoretical input we estimate that the value $B(D^0 \to K^-\pi^+)$ $=$ $(2.9 \pm 0.4)\%$ eliminates the discrepancy [25].

D. Summary and Implications

We have demonstrated that currently accepted values for $B(D^0 \to K^-\pi^+)$, namely

$$B(D^0 \to K^-\pi^+) = \begin{cases} (4.01 \pm 0.14)\% & (1994\ PDG) \\ (3.91 \pm 0.19)\% & (CLEO\ II) \\ (3.84 \pm 0.13)\% & (1995\ PDG\ update) \end{cases} \tag{2.46}$$

could be too high. The recent wrong charm $B(\overline{B} \to \overline{D}X)$ measurement of CLEO opened up a second way to determine right charm $B(\overline{B} \to DX)$. By equating the two determinations, we solved for $B(D^0 \to K^-\pi^+)$ to obtain the smaller value,

$$B(D^0 \to K^-\pi^+) = (3.50 \pm 0.21)\% \ . \tag{2.47}$$

We then demonstrated that reducing the value of $B(D^0 \to K^-\pi^+)$ enables experimental results for R_c to agree with theory and diminishes the excess of inclusive semileptonic B decays relative to the combined exclusive yields. Table IV lists the values of $B(D^0 \to K^-\pi^+)$ required to eliminate the discrepancy in each of these cases. Combining these values one obtains the weighted mean value:

$$\langle B(D^0 \to K^-\pi^+)\rangle = (3.40 \pm 0.14)\% \ .$$

Additional consequences of a lower value for $B(D^0 \to K^-\pi^+)$ are discussed in Ref. [25]. We note here that it is possible for a reduction in $B(D^0 \to K^-\pi^+)$ to affect the discrepancy between theory and measurement for R_b, the fraction of hadronic Z decays to bottom quarks. This connection follows by noting that since $B(D^0 \to K^-\pi^+)$ calibrates almost all charmed meson branching fractions, a lower value for $B(D^0 \to K^-\pi^+)$ means that a significant fraction of D^0 and D^+ decays have not been observed or properly counted. One hypothesis is that these missed decays involve high track multiplicities [26] since such decays are more difficult to fully reconstruct due to tracking inefficiencies, particle identification errors, combinatoric backgrounds and the presence of undetected neutrals. On the other hand, high charged multiplicity decays are more likely to generate a lifetime B tag at LEP and SLC since they will more likely yield the high number of significantly displaced tracks expected for B decays. We explore this possibility further in the next section.

III. R_b MEASUREMENTS

Recently the fraction R_b of Z hadronic decays to $b\bar{b}$ has been measured at LEP [27–31] and SLC [32] using a variety of methods including shape variables, multivariate techniques,

high p_T leptons, and lifetime tags to distinguish the decays of b quarks from those of lighter quarks. While each measurement is consistent, within uncertainties, with the Standard Model expectation of $R_b = 0.2155$, they combine to yield $R_b = 0.2205 \pm 0.0016$ [33] which represents a three standard deviation discrepancy. As seen in Table V, the highest precision contributions to this average are those which use lifetime B tagging. Indeed, the lifetime measurements (including the lepton + lifetime result from OPAL) yield a simple weighted mean value of $R_b = 0.2200 \pm 0.0017$ which dominates the overall result.

The procedure used for measuring R_b is to tag $Z \to b\bar{b}$ events using any of the above-mentioned methods, then subtract backgrounds as estimated from Monte Carlo (MC), and estimate the B tag efficiency either by MC or directly from data. Obtaining the B tag efficiency from data is more reliable and is possible in all cases where double tagging (tagging two B hadron decays in one event) is used. As an illustration of the procedure, if we were to ignore backgrounds, the number of tagged hemispheres N_t, (where the sphere axis is defined by the direction of the highest energy jet) and the number of double tagged events N_{tt} would be expressed as

$$N_t = 2\epsilon_b R_b N_Z \tag{3.1}$$

$$N_{tt} = C_b \epsilon_b^2 R_b N_Z \tag{3.2}$$

For a given B tagging algorithm one counts N_t and N_{tt}. N_Z is the total number of hadronic Z decays. C_b is a correlation factor which takes into account the fact that the probability of tagging a hemisphere may be correlated with whether or not the other hemisphere is tagged. Eqs. (3.1) and (3.2) can be solved for R_b and ϵ_b :

$$\epsilon_b = \frac{2N_{tt}}{C_b N_Z} \tag{3.3}$$

$$R_b = \frac{C_b N_t^2}{4N_{tt}N_Z} \tag{3.4}$$

When the B purity of the tagging algorithm is high, so that backgrounds are small, Eqs. (3.3) and (3.4) are relatively good approximations. Including backgrounds, one arrives at the following generalizations of Eqs. (3.1) and (3.2):

$$\frac{N_t}{2N_Z} = \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds}(1 - R_b - R_c) \tag{3.5}$$

$$\frac{N_{tt}}{N_Z} = C_b \epsilon_b^2 R_b + C_c \epsilon_c^2 R_c + C_{uds} \epsilon_{uds}^2 (1 - R_b - R_c) \tag{3.6}$$

As input to these equations one can use either the SM value $R_c = 0.172$ or a value measured in a separate analysis, and MC predictions for ϵ_c and ϵ_{uds} . A variety of data and MC-based studies are performed to estimate the correlation factor C_b. C_c and C_{uds} differ negligibly from unity.

We have asked whether there could be an explanation for the experimental result which does not contradict the Standard Model. Under the *assumption* that there could be an error in the result obtained for the dominant lifetime measurement technique, it follows that this error would have to be common to a number of different measurements and, as indicated by equation (3.4), would likely result from an excess of single hemisphere tags relative to double-tagged events, or from an overestimate of C_b. Due to the many subtle differences in the experiments and analyses, it is unlikely that a common error could have occurred in the estimates of C_b. There could however be a missed or incorrectly estimated background that enhances N_t and/or suppresses N_{tt}. Since the b tagging algorithms used by the experiments are of high purity, as shown in Table VI, we conclude that events with two tagged hemispheres should have extremely small non-b backgrounds. By process of elimination, one is therefore led to the possibility that some non-b source of single hemisphere tags could have been overlooked. From Eqs. (3.4) and (3.5) this would imply that one or both of ϵ_c and ϵ_{uds} are wrong.

The light quark tagging efficiency ϵ_{uds} can be studied directly with data even for the added complication of gluon radiation with splitting to $b\bar{b}$ or $c\bar{c}$ [34]. The charmed tagging efficiency ϵ_c is more difficult to determine since it depends upon the relative populations of D^o, D^+, D_s, Λ_c ..., and their decays. We can investigate the sensitivity of R_b to ϵ_c and ϵ_{uds} by plotting the variation in R_b as a function of each efficiency with all other quantities fixed at their nominal values. For simplicity we set $C_b = 1$ which then results in the following

simple expression for R_b:

$$R_b = \frac{(\frac{N_t}{2N_Z} - R_c(\epsilon_c - \epsilon_{uds}) - \epsilon_{uds})^2}{\frac{N_{tt}}{N_Z} - \frac{N_t}{N_Z}\epsilon_{uds} - R_c(\epsilon_c - \epsilon_{uds})^2 + \epsilon_{uds}^2} \tag{3.7}$$

For nominal values we choose $\epsilon_{uds} = 1.7 \times 10^{-3}$ and $\epsilon_c = 1.4 \times 10^{-2}$ which are in the mid-range of the values used by the LEP experiments (see Table VI). We assume the value $R_c = 0.172$. Finally we use $\frac{N_t}{2N_Z} = 0.055$ and $\frac{N_{tt}}{N_Z} = 0.012$ which are comparable to the values in Ref. [31] and result in $R_b = 0.22$ as quoted above for the combined lifetime measurements. Figure 1 plots R_b as a function of the change in ϵ_c and ϵ_{uds} . The discrepancy between measured and predicted values for R_b is seen to correspond to roughly a 50% increase in ϵ_{uds} from its nominal value or a 20% increase in ϵ_c . (The discrepancy is of course also removed by smaller but simultaneous upward shifts in both efficiencies.)

A review of the various measurements of ϵ_{uds} yields no obvious oversights. Our initial concern was that there could be some contribution from gluon radiation followed by splitting to $b\bar{b}$ or $c\bar{c}$. However, $g \to b\bar{b}$ occurs in only about (0.2 - 0.3)% of Z hadronic decays while $g \to c\bar{c}$ occurs in roughly 2.5% of Z hadronic decays [34–37]. Furthermore, the experiments have explicitly studied the effect of $g \to b\bar{b}, c\bar{c}$ in Z decays to light quarks and find no significant enhancement in ϵ_{uds} . Even under the assumption of a large uncertainty in the probability for this phenomenon to occur, it is not possible to achieve anywhere near the 50% shift required in ϵ_{uds} to explain the R_b discrepancy.

We next consider ϵ_c . We were unable to find explicit consideration of the possible effect of gluon radiation and splitting to $b\bar{b}$ and $c\bar{c}$ in $Z \to c\bar{c}$ events. The effect of gluon splitting in these events could be more important than in the light quark Z decays since: (i) the R_b discrepancy is removed by a smaller change in ϵ_c than would be required for ϵ_{uds} and (ii) $Z \to c\bar{c}g$ with $g \to c\bar{c}$ results in events with typically three heavy flavors in one hemisphere. Such hemispheres could be expected to have a higher than average multiplicity of significantly displaced charged tracks. The primary charm quark from the Z decay will typically remain fairly energetic in spite of having radiated a gluon, and it is then only necessary for one of the charm quarks from $g \to c\bar{c}$ to be energetic in order to have two

significantly displaced heavy flavor decays similar to that expected for B decay.

To study this phenomenon we have used the PYTHIA Monte Carlo (version 5.7) with JETSET (version 7.4) [38]. To cross-check these results we have written a toy MC based upon the differential relative rate for the process $Z^0 \to c\bar{c}g,\ g \to c\bar{c}$ calculated using an $\mathcal{O}(\alpha_s^2)$ cross section. Our calculation is more precise than the leading-log approximation at $\mathcal{O}(\alpha_s^2)$ valid only at small angles, because we wanted to also consider large-angle gluon emission. We neglected terms proportional to k^2/M_Z^2, with k^2 denoting the virtuality of the gluon. As anticipated, we find that the fraction of those hemispheres with $g \to c\bar{c}$ that contain a large number of displaced charged tracks (e.g. $N_{displaced} \geq 4$) increases dramatically. These however represent only a small fraction of all hemispheres with $g \to c\bar{c}$ and upon applying the jet probability B tag algorithm [29] we found that, on average, the tagging efficiency was not significantly higher than for hemispheres which do not contain $g \to c\bar{c}$.

Finally, as mentioned in the previous section, the accepted value for the branching ratio $B(D^0 \to K^-\pi^+)$ could be too high. One consequence would be that roughly 15% of D^0 decays would be missing. A similar argument applies to D^+ decays since the most accurate measurement of $B(D^+ \to K^-\pi^+\pi^+)$ is tied to $B(D^0 \to K^-\pi^+)$ [7]. A number of different scenarios could be proposed for the missing decays. We consider here one which could link the reduced value for $B(D^0 \to K^-\pi^+)$ to the discrepancy between the measured value of R_b and the value predicted by the Standard Model. In particular, if the missing decays were predominantly multiple charged particle modes, then it can be demonstrated that this would increase the value of ϵ_c relative to that currently assumed in recent measurements of R_b.

To demonstrate this we have performed a simple Monte Carlo study of the process $e^+e^- \to Z \to c\bar{c}$, again using the PYTHIA MC with JETSET. We have chosen the DELPHI detector for the purpose of creating a simple model of detector effects such as silicon detector acceptance and impact parameter resolution. The results would however be qualitatively the same if we were to use OPAL or ALEPH detector acceptances and resolutions. For each stable charged particle we have calculated the impact parameter (d) relative to the

e^+e^- interaction vertex. The calculated impact parameter is smeared according to the measured DELPHI resolution function [1]. The impact parameter significance is then defined as $S \equiv d/\sigma_d$ where σ_d depends on transverse momentum [39].

For lifetime B tagging we again apply the jet probability algorithm which uses impact parameter significance values of charged particle tracks to detect the presence of long-lived particles. The resulting hemisphere probability distribution we obtain for $e^+e^- \rightarrow Z \rightarrow c\bar{c}$ is shown in Figure 2 where it is compared to that obtained by ALEPH [29]. The distributions are not expected to be in strict agreement since we have not modelled detector efficiencies and acceptances in detail. Nevertheless, the agreement is good and should be adequate for this discussion. Figure 3 plots the hemisphere tagging efficiencies for all D^0 decays containing 4 or more charged particles, and for all D^+ decays containing 3 or more charged particles (normalized to the tagging efficiency for all charm hemispheres), as a function of $\log_{10}(\mathrm{P_H^{cut}})$, where $\mathrm{P_H}$ is the jet probability obtained for all charged tracks in the hemisphere. In measurements of R_b using this algorithm, a B tag is defined as a hemisphere satisfying $\mathrm{P_H} \le \mathrm{P_H^{cut}}$ where $10^{-4} \le \mathrm{P_H^{cut}} \le 10^{-2.9}$ for the various experiments. It is clear from Figure 3 that the multiple charged track modes have a significantly higher value of ϵ_c in this range of $\mathrm{P_H^{cut}}$ values. Despite the presence of fewer charged tracks, the D^+ efficiency is much higher than that of the D^0 in Figure 3, becaue of its significantly longer lifetime.

From our previous discussion, we found that the R_b discrepancy is removed by a 20% increase in ϵ_c . Relative to a nominal value of $\epsilon_c = 0.014$, this corresponds to $\epsilon_c = 0.017$. Since the charm quark hadronizes as a D^0 or D^+ roughly 60% and 25% of the time, respectively, the $\sim$ 15% of missing decays corresponds to $\sim$ 13% of all charm hemispheres. Let us assume that the remaining $\sim$ 87% of charm hemispheres have efficiency $\epsilon_c = 0.014$. We will take $\mathrm{P_H^{cut}} = 10^{-3.5}$ and assume that all missing decays are high multiplicity decays for which the efficiencies are given by Figure 3. This allows us to estimate the maximum impact on R_b. From Figure 3 at $\mathrm{P_H^{cut}} = 10^{-3.5}$, D^+ decays to three or more charged particles have a tagging efficiency $\epsilon_c^+ = 5 \cdot \epsilon_c$ while D^0 decays to four or more charged particles have

efficiency $\epsilon_c^0 = 1.5 \cdot \epsilon_c$. The adjusted charm efficiency is therefore given by:

$$\epsilon_c' = 0.87 \cdot \epsilon_c + 0.15 \cdot (0.6 \cdot \epsilon_c^0 + 0.25 \cdot \epsilon_c^+) = 1.20 \cdot \epsilon_c = 0.017$$

Thus, in the extreme where all missing decays are multiple charged particle modes, the R_b discrepancy is completely eliminated. We hasten to add that, in reality, charged modes may not represent all of the missing decays so that the effect on R_b could be smaller. In fact, at the opposite extreme, if the missing decay modes involve few or no charged particles this would lead to an increase in the final value of R_b.

IV. CONCLUSIONS

We have demonstrated that complementary determinations of $B(\overline{B} \to DX)$ can be reconciled by a downward revision in the branching ratio $B(D^0 \to K^-\pi^+)$. This revision, together with the central role played by $B(D^0 \to K^-\pi^+)$ in calibrating almost all charmed hadron yields, explains the R_c discrepancy and diminishes a problem in semileptonic B decays. We have speculated that it could also be linked to the R_b puzzle. In particular, a reduction in $B(D^0 \to K^-\pi^+)$ would mean that roughly 15% of all D^0 and D^+ decays have not been properly seen or counted. In the case where all of the missing decays involve multiple charged particle final states, we demonstrated that this leads to a higher than anticipated lifetime tag efficiency in $Z \to c\bar{c}$ events which would be adequate to bring the measured value of R_b into line with the Standard Model value of 0.2155 . We have also explicitly considered $g \to c\bar{c}$ in $Z \to c\bar{c}$ events but find that it does not enhance the lifetime tagging efficiency.

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V. APPENDIX: CHARMED BARYON PRODUCTION IN B MESON DECAYS

Accurate accounting of inclusive charm yields in B decays requires a consistent description of charmed baryon production, which is lacking in the existing literature. Several years ago it was hypothesized that the soft inclusive momentum spectrum of inclusive Λ_c production indicates that $b \to c\bar{c}s$ is the dominant source of Λ_c's in B decays [40]. The hypothesis predicted (i) large wrong-sign $\ell^- \Lambda_c$ correlations, where the lepton comes from the semileptonic decay of one B and the Λ_c from the other B in an $\Upsilon(4S)$ event; and (ii) large Ξ_c production in B decays, which at that time had not been observed and was believed to be highly suppressed [41]. Shortly afterwards, CLEO observed the first evidence of Ξ_c production in B decays (see Table I), but also found that the right-sign $\ell^+ \Lambda_c$ correlations are dominant (see Table III) [11]. CLEO measured [11]

$$r_{\Lambda_c} \equiv \frac{B(\overline{B} \to \overline{\Lambda}_c X)}{B(\overline{B} \to \Lambda_c X)} = 0.20 \pm 0.14\ . \tag{5.1}$$

Because the CLEO measurements of inclusive Ξ_c production in B decays involve large uncertainties, and their central values appear to us to be too high, this Appendix correlates Ξ_c and Ω_c production in tagged $\overset{(-)}{B}$ decays to that of the more accurately measured Λ_c. We neglect $b \to u$ transitions and use the Cabibbo suppression factor $\theta^2 = (0.22)^2$ for charmed baryon production in $b \to c\bar{u}s (b \to c\bar{c}d)$ versus $b \to c\bar{u}d' (b \to c\bar{c}s')$ transitions. The parameter $p = 0.15 \pm 0.05$ models the fraction of $s\bar{s}$ fragmentation relative to $f\bar{f}$ fragmentation from the vacuum, where $f = u, d$ or s. (This value for p was chosen to demonstrate that even a large value yields a significant reduction in Ξ_c production in $\overline{B}$ decays.)

We denote by $C_{\bar{u}d}$ the fraction of $\overline{B}$'s which decay to weakly decaying charmed baryons which come from $b \to c\bar{u}d$, and define $C_{\bar{c}s}, C_{\bar{c}d}, C_{\bar{u}s}$ analogously. Because our model allows for substantial charmless-baryon, charmless-anti-baryon production in B decays, $C_{\bar{u}d}$ is smaller, or at most equal to $B_{\bar{u}d}$ as defined in Ref. [40]. Similar comments can be made for $C_{\bar{c}s}, C_{\bar{c}d}$, and $C_{\bar{u}s}$ relative to $B_{\bar{c}s}, B_{\bar{c}d}$, and $B_{\bar{u}s}$. The simplest version of the model predicts

$$B(\overline{B} \to \Lambda_c X) = (1-p)(C_{\bar{u}d} + C_{\bar{c}d}) \tag{5.2}$$

$$B(\overline{B} \to \overline{\Lambda}_c X) = (1-p)(C_{\bar{c}s} + C_{\bar{c}d}) \tag{5.3}$$

$$B(\overline{B} \to \Xi_c X) = p\; C_{\bar{u}d} + (1-p)\; C_{\bar{u}s} + (1-p)\; C_{\bar{c}s} + p\; C_{\bar{c}d} \tag{5.4}$$

$$B(\overline{B} \to \overline{\Xi}_c X) = p\;(C_{\bar{c}s} + C_{\bar{c}d}) \tag{5.5}$$

$$B(\overline{B} \to \Omega_c X) = p(C_{\bar{u}s} + C_{\bar{c}s}) \tag{5.6}$$

$$B(\overline{B} \to \overline{\Omega}_c X) = 0 \tag{5.7}$$

The Cabibbo structure

$$C_{\bar{c}d}/(C_{\bar{c}d} + C_{\bar{c}s}) = C_{\bar{c}d}/C_{\bar{c}s'} = \theta^2 \tag{5.8}$$

$$C_{\bar{u}s}/(C_{\bar{u}s} + C_{\bar{u}d}) = C_{\bar{u}s}/C_{\bar{u}d'} = \theta^2 \tag{5.9}$$

allows us to express the six observables listed on the left-hand sides of Eqs. (5.2)-(5.7) in terms of the two unknowns $C_{\bar{u}d}$ and $C_{\bar{c}s}$. The latter are in turn obtained from the two measurements involving inclusive Λ_c production in B decays, namely Y_{Λ_c} and r_{Λ_c}, as follows :

$$\frac{C_{\bar{u}d}}{Y_{\Lambda_c}} = \frac{(1+\lambda^2 - \lambda^2 r_{\Lambda_c})}{(1-p)(1+\lambda^2)(1+r_{\Lambda_c})}\;, \tag{5.10}$$

$$\frac{C_{\bar{c}s}}{C_{\bar{u}d}} = \frac{r_{\Lambda_c}}{1+\lambda^2(1-r_{\Lambda_c})}\;, \tag{5.11}$$

where

$$\lambda^2 = \frac{\theta^2}{|V_{cs}|^2} = \frac{\theta^2}{\left(1 - \frac{1}{2}\theta^2\right)^2} \; . \tag{5.12}$$

The inclusive $\overset{(-)}{\Xi}_c, \overset{(-)}{\Omega}_c$ yields in $\overline{B}$ decays are thus correlated to inclusive $\overset{(-)}{\Lambda}_c$ production,

$$\frac{B(\overline{B} \to \Lambda_c X)}{Y_{\Lambda_c}} = \frac{1}{1 + r_{\Lambda_c}} \; , \tag{5.13}$$

$$\frac{B(\overline{B} \to \overline{\Lambda}_c X)}{Y_{\Lambda_c}} = \frac{r_{\Lambda_c}}{1 + r_{\Lambda_c}} \; , \tag{5.14}$$

$$\frac{B(\overline{B} \to \Xi_c X)}{Y_{\Lambda_c}} = \frac{C_{\bar{u}d}}{Y_{\Lambda_c}} \left\{ p + (1-p)\lambda^2 + \frac{C_{\bar{c}s}}{C_{\bar{u}d}}(1 - p + p\lambda^2) \right\} \; , \tag{5.15}$$

$$\frac{B(\overline{B} \to \overline{\Xi}_c X)}{Y_{\Lambda_c}} = \frac{C_{\bar{u}d}}{Y_{\Lambda_c}} \, \frac{C_{\bar{c}s}}{C_{\bar{u}d}} \, p(1 + \lambda^2) \; , \tag{5.16}$$

$$\frac{B(\overline{B} \to \Omega_c X)}{Y_{\Lambda_c}} = p \frac{C_{\bar{u}d}}{Y_{\Lambda_c}} \left(\lambda^2 + \frac{C_{\bar{c}s}}{C_{\bar{u}d}} \right) \; , \tag{5.17}$$

$$B(\overline{B} \to \overline{\Omega}_c X) = 0 \; . \tag{5.18}$$

We have taken p to be a universal quantity and have assumed that the initially produced charmed baryon retains its charm [and when applicable, strange] quantum number[s] through to its weakly decaying offspring. This is not justified but is conservative in that it yields an upper limit for $baryon_c$ production in B decays. We typically expect the initially produced charmed baryons (via $b \to c$) to be highly excited, while this is not expected of their pair-produced antibaryons (via $b \to \bar{u}$ or $b \to \bar{c}$) [42]. That a sizable fraction of these highly excited charmed baryons could break up into a charmed meson, a charmless baryon, and additional debris is irrelevant to our discussion which focuses on weakly decaying charmed baryon production in B decays. In contrast, it is important to note that $\Xi_c^r \to \Lambda_c \overline{K} X$ could occur significantly [the superscript r denotes excited resonances]. This introduces an additional mechanism for Λ_c production in $\overline{B}$ decays, which may help explain the small measured value of r_{Λ_c}. It also decreases the naive estimate for weakly decaying Ξ_c production. Because our predictions have not incorporated such effects, they should be viewed strictly as upper limits for Ξ_c production in $\overline{B}$ decays.

TABLES

TABLE I. Inclusive Charmed Hadron Production in B Decays as Measured by CLEO

T	$Y_T \equiv B(\overline{B} \to TX) + B(\overline{B} \to \overline{T}X)$	Reference
D^0	$(0.645 \pm 0.025)\left[\frac{3.91\%}{B(D^0 \to K^-\pi^+)}\right]$	[43]
D^+	$(0.235 \pm 0.017)\left[\frac{9.3\%}{B(D^+ \to K^-\pi^+\pi^+)}\right]$	[43]
D	$(0.883 \pm 0.038)\left[\frac{3.91\%}{B(D^0 \to K^-\pi^+)}\right]$	
D_s	$(0.1211 \pm 0.0096)\left[\frac{3.5\%}{B(D_s \to \phi\pi)}\right]$	[44]
Λ_c	$(0.030 \pm 0.005)\left[\frac{6\%}{B(\Lambda_c \to pK^-\pi^+)}\right]$	[45]
Ξ_c^+	0.020 ± 0.007	[46]
Ξ_c^0	0.028 ± 0.012	[46]

TABLE II. Absolute Branching Ratios of Key Charm Decays

Mode	BR [in %]	Reference
$D^0 \to K^-\pi^+$	3.91 ± 0.19	[5]
$D_s \to \phi\pi$	3.5 ± 0.4	[6]
$\Lambda_c \to pK^-\pi^+$	6.0 ± 1.5	[12]

TABLE III. Inclusive Charmed Hadron Production in Tagged B Decays as Measured by CLEO

Observable	Value	Reference
$r_{\Lambda_c} \equiv \frac{B(\overline{B} \to \overline{\Lambda}_c X)}{B(\overline{B} \to \Lambda_c X)}$	0.20 ± 0.14	[11]
$r_D \equiv \frac{B(\overline{B} \to \overline{D} X)}{B(\overline{B} \to DX)}$	0.107 ± 0.034	[9]
$f_{D_s} \equiv \frac{B(\overline{B} \to D_s^+ X)}{Y_{D_s}}$	0.172 ± 0.083	[47]

TABLE IV. Extracted Values of $B(D^0 \to K^-\pi^+)$.

Analysis		$B(D^0 \to K^-\pi^+)$
$B(\overline{B} \to DX)$		$(3.50 \pm 0.21)\%$
$R_c(D^{*+})$		$(3.35 \pm 0.25)\%$
R_c(charm counting)		$(3.67 \pm 0.36)\%$
Semileptonic BR's		$(2.9 \pm 0.4)\%$
ALL		$(3.40 \pm 0.14)\%$

TABLE V. R_b Results as of the Brussels EPS-HEP-95 Conference

Experiment	Data Set(s)	Measurement Type	R_b ($R_c = 0.172$ Fixed)
ALEPH	1992	Lifetime	$0.2192 \pm 0.0022 \pm 0.0026$
DELPHI	1992-3 prel.	Lifetime	$0.2216 \pm 0.0017 \pm 0.0027$
DELPHI	1992-3 prel.	Mixed	$0.2231 \pm 0.0029 \pm 0.0035$
DELPHI	1992-3 prel.	Multivariate	$0.2186 \pm 0.0032 \pm 0.0022$
OPAL	1992-4 prel.	Lifetime + lepton	$0.2197 \pm 0.0014 \pm 0.0022$
ALEPH	1990-1	Event Shape	$0.228 \pm 0.005 \pm 0.005$
SLD		Lifetime	$0.2171 \pm 0.0040 \pm 0.0037$
L3	1991	Event Shape	$0.222 \pm 0.003 \pm 0.007$
LEP		Lepton Fits	0.2219 ± 0.0039
LEP+SLD		**Lifetime Fits**	$\mathbf{0.2200 \pm 0.0017}$
ALL			$\mathbf{0.2205 \pm 0.0016}$

TABLE VI. Purity, efficiencies and correlation values.

Experiment	B Purity	ϵ_b	ϵ_c	ϵ_{uds}	C_b
ALEPH	0.96	0.26	1.18×10^{-2}	0.88×10^{-3}	0.943
DELPHI	0.92	0.21	1.60×10^{-2}	2.52×10^{-3}	0.952
OPAL	0.94	0.23	1.37×10^{-2}	1.01×10^{-3}	1.006
SLD	0.94	0.31	2.30×10^{-2}	0.87×10^{-3}	0.995

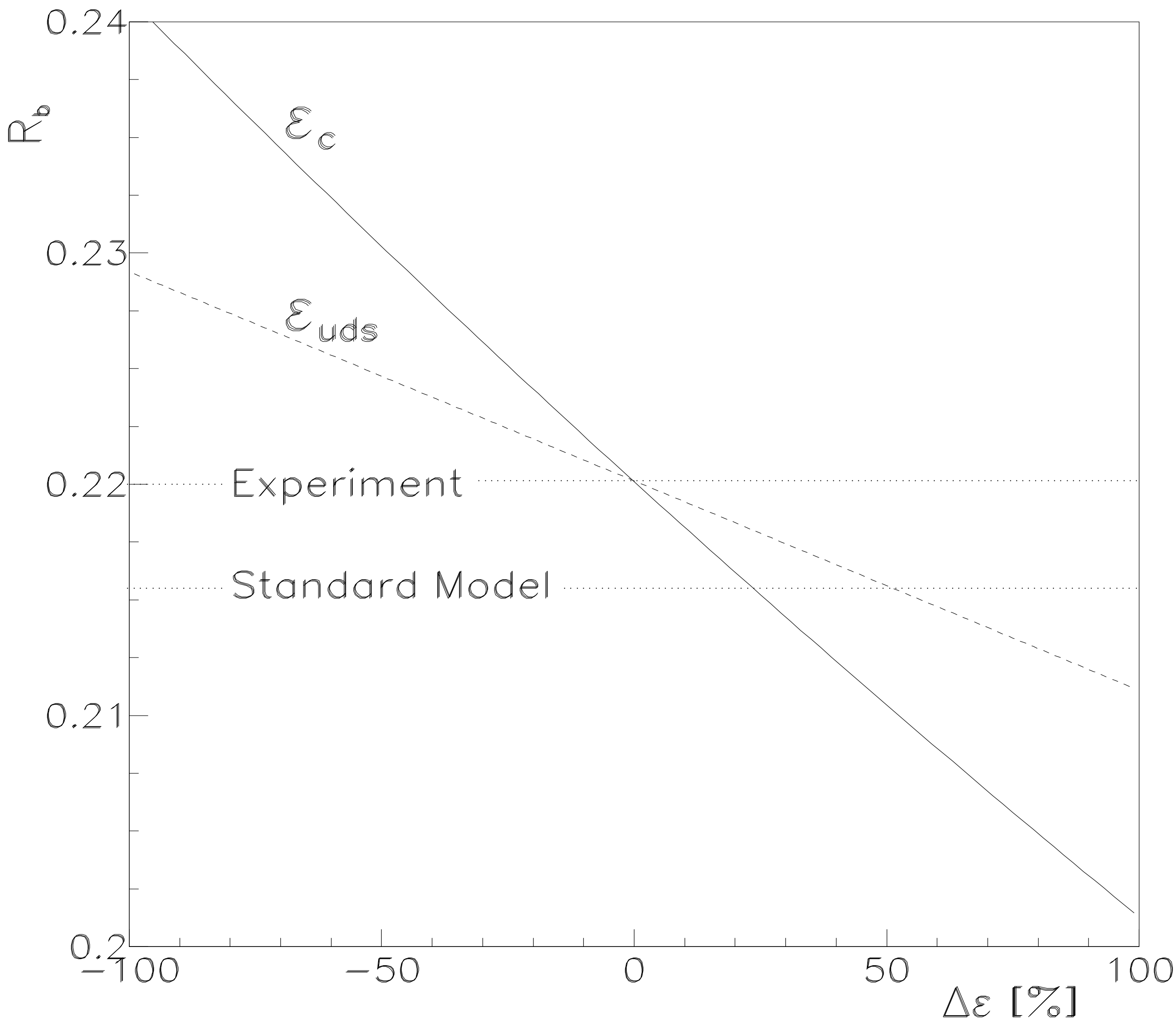

FIG. 1. R_b as a function of the change in the efficiencies ϵ_{uds} and ϵ_c varied separately.

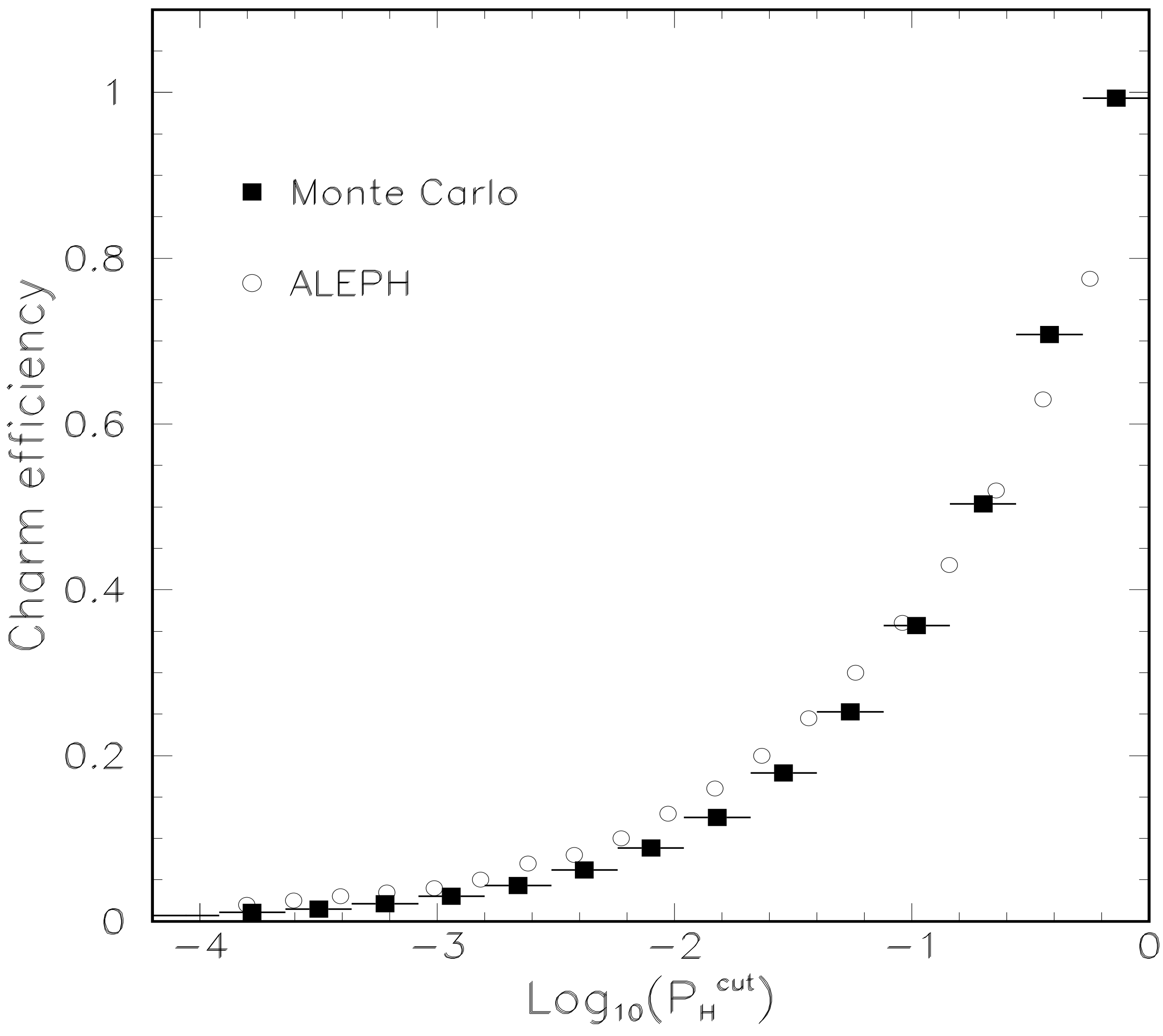

FIG. 2. The tag efficiency versus the Log of the probability cut ($\mathrm{Log}_{10}(\mathrm{P_H})$) for Monte Carlo $e^+e^- \to Z \to c\bar{c}$ events used in this paper (open circles) as compared with that obtained by ALEPH (solid squares)

.

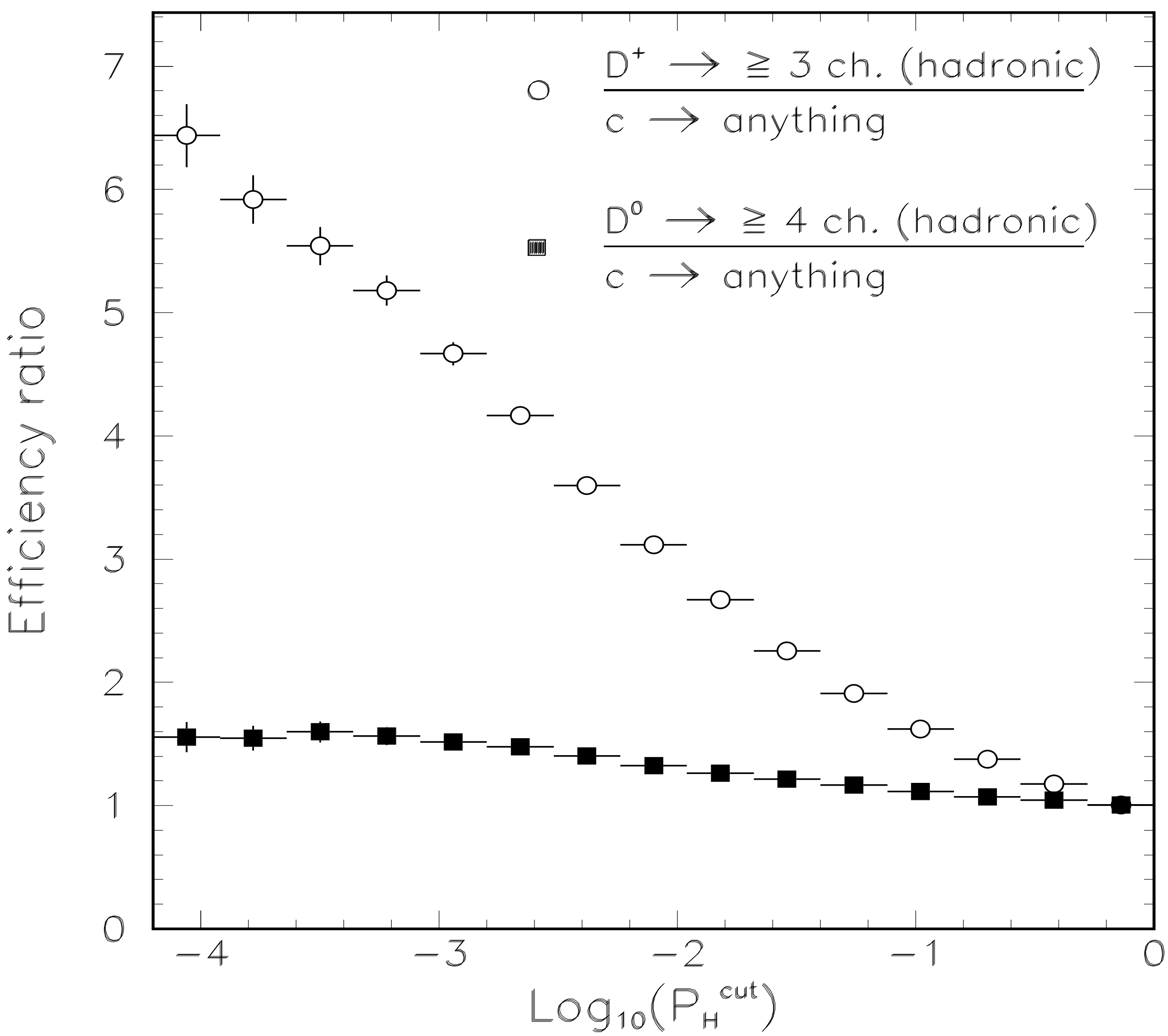

FIG. 3. The ratio of the tagging efficiency for D^0 hadronic decays containing at least 4 charged particles to the decays of all charmed hadrons (black squares) and the similar ratio for D^+ hadronic decay modes containing at least 3 charged particles (open circles) as a function of Log_{10} of the cut on hemisphere jet probability $\mathrm{P_H^{cut}}$.

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